Designing Intelligent Food, Energy & Water Systems (DIFEWS)

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Executive Summary

In semi-arid regions, like the Western United States, the intertwined stressors of climate variability, persistent waste, continued pollution and shifting demographics are creating trilemmas in linked food, energy, and water (FEW) systems. The effects of these trilemmas are environmental, economic, and social. For example, on-going drought in California has reduced the availability of water for both renewable hydropower and agriculture. The resulting water-use trade-offs have left fields fallow, increased energy and food prices, and depleted groundwater supplies. To develop the science, technology, and policy to resolve trilemmas in FEW systems, University of California at Berkeley hosted the National Science Foundation funded Developing Intelligent Food, Energy, and Water Systems Workshop (DIFEWS) on September 28-29, 2015. The workshop brought together investigators in the physical, natural, computer, and social sciences, along with engineers, economists, policy-makers, and practitioners from diverse backgrounds.

The workshop identified three key challenges for FEW systems in California and beyond:

Challenge 1: Closing the Loop Across FEW Systems

There are many inputs and outputs of agricultural, water, and energy systems that should be designed and managed to minimize inputs, maximize outputs, and minimize provision inequality. Important research opportunities identified include: reducing edible food waste along the supply chain; capturing and reusing nutrients in organic waste products; recovering heat in the food sector; utilizing food waste and wastewater as sources of renewable energy; capturing waste water and tailoring treatment quality to targeted end use.

Challenge 2: Resolving Spatiotemporal Disconnects in FEW Systems

Supply and demand for FEW resources are largely uncoupled in time and space. Important research challenges identified include: optimizing storage in ever-lengthening food cold chains; development of small-scale hydropower technologies and necessary control systems to allow for distributed generation of electricity in the agricultural sector; developing better soil management techniques, creating distributed smart irrigation systems; developing the technology to increase groundwater storage by creating “frackquifers”; and encouraging institutions and enabling policies for the integrated management of FEW systems.

Challenge 3: Creating Actionable Information

FEW systems involve a variety of actors whose behaviors, decisions, and actions are impacted by economics, policy, information, social and cultural factors, and physical access to technologies and resources. Important research opportunities identified included: developing cyberphysical infrastructure and lifecycle methodologies to collect integrated information and data on food, energy and water and investigating ways to best translate FEW information to inform and influence a diversity of stakeholders.

Beyond the research challenges identified, fully understanding and ultimately managing FEW systems will require a combination of (i) discovery driven disciplinary science at the frontiers of the physical, natural, and social fields; (ii) integrative research that unites these disparate disciplines; and (iii) the training and formation of interdisciplinary teams.

Inextricably Linked Food, Energy, and Water in California and Beyond

Food, energy, and water (FEW) systems are inextricably linked. Particularly in semi-arid regions such as the western U.S., as well as large swaths of China, India, and Brazil, energy and agriculture are dependent on large-scale hydrological systems. In these regions, water supply and demand are disconnected spatially. The global nature of food, including the associated agricultural, processing, and distribution systems, further intensifies FEW challenges.

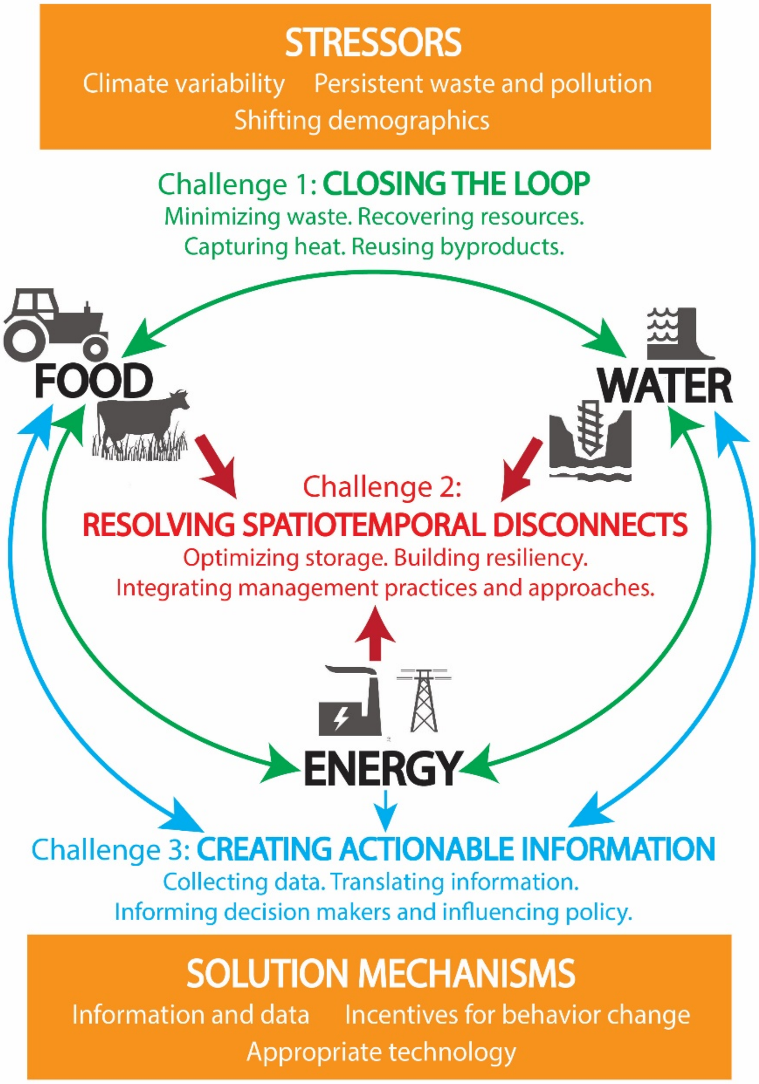

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Figure 1: Interconnections between Food, Energy, and Water. Three grand challenges for overcoming the FEW trilemma identified by workshop participants are shown with color-coded arrows indicating the effect that solving each will have on the three FEW systems

This is especially evident in California, where the sparsely populated north supplies more than 75% of the water, yet 80% of the demand lies in the growing urban and agricultural centers of the south (McEwan et al. 2014). To connect these distal regions, the state constructed an extensive network of dams, tunnels, canals, aqueducts, pumping stations, storage facilities, and hydroelectric power plants during the so-called "hydraulic era" of 20th century (Hanak et al. 2011). However, the pumping and distribution of water has proven to be highly energy intensive, especially over the large distances required for residential and agricultural use in California. For water pumping alone, the California State Water Project consumed 8.55 million MWh in 2011 (McEwan et al. 2014), an amount corresponding to the energy needed to power 1.2 million homes for a year (US Energy Information Administration 2009).

As the largest agricultural producer in the US, California faces FEW challenges that extend far beyond its own borders and into domestic and international markets (USDA 2015b). Of the approximately $46 billion in agricultural products produced in California each year, more than half are exported internationally. Inextricably interconnected with the export of this food are the water and energy resources required to use and transport it (Fulton & Cooley 2015). While dairy, fruit, vegetables, and nuts are typically considered to be the state's most lucrative agricultural exports, the economic and environmental impacts of their production on energy and water systems are frequently overlooked; thus, many externalities of interconnected global agricultural markets remain hidden. Agriculture and energy production require significant quantities of water and, in addition, often result in decreased water quality. The impacts are enormous: agricultural uses account for 40% of California's total water supply and 80% of its developed and dedicated water supply (i.e., water specifically allocated for agriculture, urban, and certain other uses) (Public Policy Institute of California 2015).

With the variety, complexity, and immediacy of its FEW challenges, California presents an instructive opportunity for studying issues that will increasingly be faced by the nation and the world. Toward this end, University of California, Berkeley hosted a National Science Foundation funded workshop on September 28 and 29, 2015, to discuss Intelligent Food, Energy, and Water Systems. This interdisciplinary workshop explored the synergies across four areas: agroecology; sustainable environmental engineering; consumer behavior; and the application of cyber-physical systems research to FEW systems. Participants came from near a dozen departments at UC Berkeley and more than a dozen other institutions and agencies, including UC Davis, Stanford University, Pacific Institute, University of Toronto, and California Department of Food & Agriculture. We present the outcomes of the workshop in this paper and graphically in Figure 1.

Intertwined Food, Energy, and Water Stressors

Climate Variability

Both natural and human-induced climate variability stress the FEW systems. The current drought in the Western United States, now in its fifth year, has revealed a number of weaknesses in existing systems, policies, and practices. As of 2014, ninety-nine percent of California's agricultural landscape experienced severe, extreme, or exceptional drought (Wallander 2014). Reduced precipitation, in combination with warmer winters and summers, has significantly decreased snowpack and reservoir capacity. Of the 3.2 million irrigated acres of croplands that rely on off-farm water supplies, an estimated 540,000 acres are being left fallow due to the reduced snowpack in the Sierras and curtailment of Colorado River water delivery (California Department of Water Resources 2015; Carlton 2015; UC Davis 2015). The net water shortage due to the 2015 drought is estimated at approximately 2.7 million acre-feet (after accounting for increased groundwater withdrawals to offset surface supply shortages), with the direct costs of the drought are predicted to be $1.84 billion (UC Davis 2015), including the loss of approximately 10,100 seasonal jobs (Howitt et al. 2015). If drought conditions continue, their impacts are projected to increase by 6% annually from 2015 to 2017, with the gradual decline in the water table contributing further to increased costs of a prolonged drought (Howitt et al. 2015).

Beyond its impact on agriculture, reduced water supply also affects renewable energy generation. According to a recent study by the Pacific Institute, the ongoing drought reduced the share of hydroelectricity in California's electricity mix from its long-term average of ~18% to less than 12% in 2012 (Gleick 2015). As a result, ratepayers spent $1.4 billion more in 2012 than in an average year. In addition, greenhouse gas emissions during the drought increased by 1.7% statewide in 2012, reversing the trend of their reduction during the past several years (Gleick 2015).

California has experienced lower than average precipitation since 2007 (Cook et al. 2015). Although current El Niño conditions may offer a temporary respite, the amount and nature of the rainfall is unlikely to sufficiently negate the effects of California's long precipitation deficit. California's largest source of fresh water (typically, 30% of total supply), the Sierra snowpack located in the northern and eastern regions, is now at a 500-year low (Belmecheri et al 2015). The snowpack naturally provides significant seasonal water storage, melting in the spring and early summer when water demands increase. Historical data indicate that frequent multi-year droughts have been common in the west over the past millennium (Griffin et al. 2014), and some suspect that drought may be the "new normal" in the western United States. Human-induced climate change is likely to amplify the natural shift towards a drier western US characterized by droughts of increasing severity and frequency (Diffenbaugh et al. 2015).

Persistent Waste and Continued Pollution

Waste and pollution are endemic to our current FEW systems. Approximately 40% of edible food harvested in the United States is wasted along the supply chain, without even taking into account food left on the farm (Buzby et al. 2014; Hall et al. 2009). Embedded in this wasted food is 25% of the nation's freshwater consumption and 3% of the U.S. energy budget (Buzby et al. 2014; Hall et al. 2009). Further contributing to unnecessary waste are food expiration labels such as "best by," "use by," or "sell by" dates that are based more on aesthetics than on food safety and thus lead to consumer confusion (Hall & Osses 2013). The modern cold chain of refrigeration and freezing is a double-edged sword, slowing food spoilage but encouraging over-consumption which, in turn, can exacerbate waste.

Our water systems are also plagued by waste. Consumers use water inefficiently in homes, in businesses, and on farms. Water losses in California's water distribution networks amount to an estimated 10% of the state's urban water supply (Water Systems Optimization 2009). The vast majority of the treated water supply is potable, even for applications in which non-potable water would suffice (e.g., flushing toilets; irrigating landscapes). Excess treatment consumes energy and chemicals unnecessarily. In addition, in California water rights are over-allocated while water use is under-reported and largely unquantified, complicating the understanding and management of the state's water system (Grantham & Viers 2014).

Waste is also pervasive in energy systems. Excess energy is lost from all systems in the form of heat, which could be captured for other uses. Water and energy are often produced in centralized plants located far from the areas of demand. Both water and energy systems are rife with losses; longer transmission distances compound those problems. Transmission losses for distributed solar photovoltaics average approximately 1-2%, while losses for more remote generation range from 5-10% (Jacobson et al. 2015).

In addition to waste, pollution pervades FEW systems. In California, excessive groundwater pumping rates have polluted productive soils by increasing their salinity through saltwater intrusion into a lowered water table (Schoups et al. 2005). In our urban environments, the legacy of industrial chemical use has left soil contaminated with arsenic and lead, thus limiting opportunities for urban agriculture to contribute to safe solutions for FEW challenges (Wortman and Lovell 2013; Albanese and Cicchella 2013). More broadly, our dependence on synthetic fertilizer, herbicides, pesticides, and waste has polluted soil, water, and air. Fertilizer overuse and animal waste are the primary regional contributors to nitrate pollution in groundwater aquifers, especially in the Tulare Lake Basin and the Salinas Valley of Central California (UC Davis 2012). Because nitrates reach aquifers slowly, these problems are predicted to worsen for decades even if we control the sources today. Fertilizers also contribute to air pollution through conversion by natural processes to NO_x and N_2O, a criteria air pollutant and a powerful greenhouse gas, respectively.

Shifting Demographics

Changes in current demographics will multiply the effects of FEW stressors, including climate variability, waste, and pollution. The future world will broadly be more urban and affluent (United Nations Department of Economic and Social Affairs 2014). California' population is rapidly approaching 50 million, and the world may reach 10 billion within the present century (Gerland et al. 2014). As communities become more urban and cities swell, the distance between supply and demand for water and food will increase. Urban populations require longer food chains, consume more packaged food, and extend the length and reach of the cold chain, enabling the consumption of niche foods and of fresh fruit and vegetables year-round. Longer food changes are more vulnerable to climate disruptions and natural disasters (USDA 2015a). A more urban and affluent population increases waste and pollution (Tacoli 1998). In addition, population growth in urban areas can surpass growth in water storage capacity (Macdonald et al. 2014). Finally, growth of the urban population creates challenges to food security and food sovereignty. As stated by the director of the United National Department of Economic and Social Affairs, “managing urban areas has become one of the most important development challenges of the 21st century. Our success or failure in building sustainable cities will be a major factor in the success of the post-2015 UN development agenda” (United Nations Department of Economic and Social Affairs 2014).

This growing population, while generally more urban and affluent, will remain characterized by concentrated pockets of poverty and unequal access to FEW resources. Stresses on FEW systems tend to disproportionately affect lower-income households. Those in the lowest 20th income percentile spend 67% of their income directly on food, water, and energy, compared with 11% for the highest 20th percentile (U.S. Bureau of Labor Statistics 2015). In the face of such disparities, increases in water, food, and energy prices could be devastating for many families. Nearly 40% of low-income households already suffer from food insecurity (Coleman-Jensen et al. 2014). If future droughts reflect past trends, we can expect an associated increase of 3%-4% in retail fruit and vegetable prices (Kuhns 2014), which will increase food insecurity of households at or below the poverty line. Research has shown that households with high food insecurity are less likely to consume high quality diets (Rose 1999) and that children living in these households are more likely to exhibit compromised psychosocial functioning (Olson 1999).

Food, Energy, and Water Challenges & Mechanisms for Solution

The management of FEW systems in California and beyond will be increasingly pertinent and complex in the face of ongoing stresses. Managing these three systems in a connected and cooperative manner will help mitigate the effects of climate variability and demographic changes while reducing waste and pollution. FEW systems in and beyond California face three key challenges:

Challenge 1: Closing the Loop Across FEW Systems

There are many inputs and outputs of agriculture, water systems, and energy systems that should be designed and managed to minimize inputs, maximize outputs, and minimize inequality. By *closing the loop,* we can reduce negative environmental impacts while still meeting the basic needs of the system, whether it be food production, water/wastewater treatment, or energy production.

Challenge 2: Resolving Spatiotemporal Disconnects in FEW Systems

Supply and demand for FEW resources are often uncoupled in time and space. To mitigate these spatiotemporal mismatches, innovative approaches to short- and long-term water storage systems and distributed renewable energy generation are needed, along with more widespread adoption of resilient farming practices. Integrated management practices among food, energy, and water systems are also required.

Challenge 3: Creating Actionable Information

FEW systems involve a variety of actors whose behaviors, decisions, and actions are impacted by economics, policy, information/knowledge, social and cultural factors, and physical access to technologies and resources. It is important to understand how these actors interact with policies, technologies, and each other if we are to successfully engage all stakeholders in moving towards a more intelligent and sustainable FEW network.

We have identified three broad mechanisms to address the challenges delineated above in a systematic fashion. The integration of these mechanisms will facilitate the sustainable management of FEW systems. First, useful *information and data* must be collected, understood, and shared by appropriate stakeholders. Second, *appropriate technologies* should be developed and used. Third, *incentives for behavioral change* will be needed to support action by FEW stakeholders and consumers.

The three challenges are discussed in detail in the following sections and the paper concludes with some broader comments on how to stimulate interdisciplinary research in the FEW systems.

Challenge 1: Closing the Loop Across FEW Systems

Currently, FEW systems are generally extractive in nature, require resource-intensive inputs, and produce byproducts that negatively impact human health and the environment. Closing the loop in FEW systems -- that is, preventing waste and harmful byproduct generation, and recovering and reusing waste products -- can significantly alleviate negative impacts on environmental and human health while meeting human needs and promoting economic growth.

Untapped opportunities exist for closing the loop across multiple resources in the FEW nexus, including edible food, nutrients, water, energy, labor, and finance. By targeting the lifecycles of these resources, we can close loops in both urban and rural communities, implementing solutions while also benefitting other resources. Integrated management of FEW systems will be key to the successful closure of loops; where possible, waste products from one resource should feedback efficiently into the production of other resources in the nexus. Generally speaking, the solutions involve techniques that improve resource efficiency and recovery. Better education and communication of innovative, integrated FEW policies are necessary in order for such efforts to truly succeed in "closing the loop." The potential of using waste materials has not yet been fully realized due to a number of factors: logistics of proper management; costs; limited integration into existing practices; lack of public acceptance; and sometimes-conflicting environmental regulations (Westerman & Bicudo 2005). Each of these provides a potential avenue for optimization.

i) Closing the Food Loop

Up to 40% of edible food harvested in the United States is wasted along the supply chain from distribution to consumer, with further significant losses due to food and non-edible components such as pits and peels being left on farms during production (Buzby et al. 2014; Hall et al. 2009). Approximately 25% of U.S. freshwater consumption, 4% of U.S. greenhouse gas emissions, and 2% of the U.S. energy budget is embedded in this wasted food. When food is wasted, not only is potential profit lost, but the investment of additional tax dollars and/or private funding is required for proper waste disposal. Wasted food costs the U.S. economy an estimated $165 billion per year (Buzby & Hyman 2012). Causes of food waste on farms include over-planting, labor costs, market prices, aesthetics, spoilage, and trimming. Once food leaves the farm, further losses occur due to over-purchasing resulting from USDA grading and marketing standards, long supply chains, climate and weather, packaging requirements, retailer contracts with farmers, and consumer behavior (Bloom 2010; Gunders 2012; Buzby et al. 2014; Hodges et al. 2010; Natural Resources Defense Council 2012). Because the causes are complex, significantly reducing wasted food will require integrated solutions in the areas of technology, consumer behavior, and public policy.

Despite the substantive volume and impact of on-farm food waste, there are no reliable metrics to quantify and track how much food is left behind in the field or on the farm. National-level data includes only post-harvest measurements (Natural Resources Defense Council 2012; Buzby et al. 2014) and is of variable quality, lacking sufficient detail to identify losses by food type or reason. While the absence of consistent accounting and measurement is a barrier to reducing food waste, technological advances can help address this issue. Smart monitoring systems, remote sensing, and precision agriculture technologies may aid in quantifying on-farm food waste (Gebbers & Adamchuk 2010; Ali 2011).

Implementing policies that prevent food waste on farms would effectively increase agricultural outputs with little-to-no increase in on-farm inputs. Reducing food waste both reduces negative environmental impacts of production and addresses global concerns about increasing pressures on food supply for an increasing population and global middle class (The Global Commission on the Economy and Climate 2014; Coleman-Jensen et al. 2013). Food that would have been converted to compost or tilled back into soils can instead be captured for human consumption through gleaning (secondary harvesting of already harvested fields), improved harvesting practices, and food donation (The Global Commission on the Economy and Climate 2014).

Edible food waste can also be reduced if consumers have more of a stake in their own food production, as exemplified by the movements for food sovereignty and urban agriculture. Food sovereignty is defined as the “right of local populations to define their own agricultural and food policy,” with a focus on common social, environmental, and agricultural principles and practices (Wittman 2009). Waste from a disrupted system of producers and consumers also creates social and ecological problems. For instance, issues with the distribution of potentially edible food contribute to hunger as well as to negative environmental impacts related to excess production (Wittman 2009). FEW decision-makers should work with such sustainability-focused food movements in implementing, integrating, and scaling solutions to reduce food waste.

ii) Closing the Nutrient Loop

Most organic waste products (e.g., manure, wastewater, food waste, crop residuals) are managed with the goal of minimizing the impacts of their disposal rather than harvesting their potentially useful components. For example, more than 95% of food waste in the municipal solid waste stream is sent to landfills, further localizing the impacts. Only 5% is composted or anaerobically digested for nutrient and energy recovery (U.S. Environmental Protection Agency 2014). Organic wastes and wastewater contain nutrients that can—if managed properly through composting and other techniques—improve soil quality, increase soil water retention, and reduce chemical inputs such as fertilizers (Westerman & Bicudo 2005; Martínez-Blanco et al. 2013).

Healthy soil is critical to the food production system, but soil quality is being degraded worldwide. Nutrients are removed from the soil in the form of food (much of which is wasted) and are not reintroduced via proper crop rotation or cover cropping, for example. Rather than improving soil fertility in the long-term, excess nutrients from fertilizers often runoff from agricultural lands, polluting surface water supplies and causing algal blooms. Such fertilizer pollution has consequences for the environment, such as eutrophication, as well as for human health, including the increased risk of 'blue-baby" syndrome (Knobeloch et al. 2000). The significant environmental and human health consequences of fertilizer runoff can be reduced by closing the nutrient loop via integrated FEW systems management. Capturing waste and recovering the nutrients at multiple points along the food supply chain could improve soil productivity and fertility, enhance water quality, and reduce greenhouse gas emissions (N_2O and CH_4).

Where food waste cannot be reduced, the loop can be closed by diverting streams from landfills to composting or treatment facilities to produce a valuable agricultural product that reintroduces nutrients to the system. Farmers in Marin County, California, collect manure from cattle ranching operations and spread it on their lands as compost. This localized nutrient-recycling approach reduces runoff pollution from large manure piles, promotes healthy soils on rangeland, and sequesters carbon from the atmosphere into stable soil reservoirs (Marin Carbon Project 2008). However, broader implementation of these practices and increased uptake of related policies are currently hindered by confusing municipal waste codes and by the public perception of these practices as a health concern.

Urban wastewater contains nutrients that can be recovered for agricultural uses. Nutrient recovery technologies for use at large and small scales are being studied for application in agriculture and urban systems. They include home-sized biogas unit that turn organic waste into cooking fuel and fertilizer, as well as in-stream bioreactors (Markham 2015, Robertson & Merkley 2009, Guanglei & Ting 2014, Williams et al. 2015). Increased integration of the urban water and agricultural sectors may increase collaboration and technology transfer and, ultimately, improve outcomes for both systems. For example, municipal wastewater treatment plants (WWTP) contribute two thirds of the nutrients that run into the San Francisco Bay, substantially contributing to ecological damage and wasting valuable nutrients (Lono-Batura et al. 2012). The San Francisco Bay Water Board is considering limiting the nutrients that can legally be discharged from 30 municipal WWTPs. If these limits are implemented, the utilities will have to expand their already complex centralized WWTPs to include expensive and energy-intensive nutrient removal. The debate over policies for implementing these changes presents an ideal opportunity to examine the use of emerging, decentralized technologies (e.g. source-separating toilets) that recover nutrients from more concentrated streams (e.g., urine) for agricultural use (Larsen et al. 2009). Pioneering research in this area is being conducted at UC Berkeley, where scientists are adapting nutrient treatment and recovery technologies that were initially developed for swineries (Kizito et al. 2015; Desloover et al. 2012) and applying these for use in source-separating toilets that may help close the nutrient loop in cities (Tarpeh 2015).

iii) Closing the Energy Loop

Food, water conveyance, and wastewater systems use significant amounts of energy but are also potential sources of renewable energy. Wastewater, along with organic waste from agricultural and municipal wastes, can be used to provide energy in the form of electricity, gas, or heat. Over 90 billion cubic feet of biogas (methane) per year could be feasibly generated from the anaerobic digestion of manure, food waste, biosolids (sewage sludge), leaves, and grass in combination with landfill gas collection (Williams et al. 2015).

However, only a small portion of these organic materials are currently employed for beneficial uses (energy, heat, nutrient, or water recovery). A 2012 survey of wastewater utilities indicates that approximately one thousand large WWTPs (processing more than one million gallons a day of wastewater) in the U.S. use biogas captured from anaerobic digesters to produce energy (Qi 2013). Unfortunately, most of these operations do not achieve complete capture. In addition, they flare some methane, a potent greenhouse gas (Lono-Batura et al. 2012). While burning off methane to carbon dioxide reduces the contribution of methane to global warming, it also wastes potential biogas energy that could be obtained from it.

Successful case studies have garnered increased attention for waste as an energy resource. An energy-generation plant operated by East Bay Municipal Utility District (EBMUD) in California has drastically improved its energy management by closing the loop on food and agricultural waste. As a result, EBMUD not only supplies its own energy, but also provides electricity back to the grid (Chakrabarti et al. 2011a). Trucks of food, agricultural, and other waste are delivered daily to provide high-strength and/or more concentrated organic waste to EBMUD's anaerobic digesters, thus enhancing their biogas production and subsequent electricity generation. This is a cost-efficient but under-utilized way for WWTPs with excess digester capacity to integrate waste from another system in the FEW nexus to enhance energy production (Chakrabarti et al. 2011b). If the digester sludge is disposed on farmland, the process can also return nutrients to the soil.

Biogas recovery from anaerobic digesters benefits from economies of scale. For WWTPs, which typically have a dilute influent stream, biogas recovery has been considered economically unfeasible for plants with capacities smaller than 1 million gallons per day. In California's Central Valley, air emission control requirements and high technology costs have prevented the widespread use of on-farm anaerobic digesters (Johnson 2015). As of May 2015, there were 247 agricultural digesters operating in the U.S. (Kosusko 2015). Only 19 were located in California, a surprisingly low number given the scale of the industry. However, small successful applications do exist. In addition, other decentralized technologies such as gasification and the use of biodigesters are emerging for urban wastewater systems that may have applications for agricultural waste (Lumley et al. 2014; Markham 2015).

Barriers that prevent implementation of these technologies should be studied. Research is needed to identify the conditions required to expand anaerobic waste treatment at smaller scales. Integrating management between and combining waste streams among multiple farmers, energy, and urban water systems may produce the waste characteristics and scale necessary for these energy systems to cost-efficiently perform as well as or outperform EBMUD. This will require careful collaborative policies and mechanisms to ensure an equitable and profitable sharing arrangement, regulatory compliance, and efficient operations and maintenance.

Recovering heat is an emerging area of research for food (Law et al. 2013), energy (Gewald et al. 2014; Wang et al. 2012), and water (Daigger 2009) systems. A nationwide analysis identified the food sector as a good candidate for more efficient steam systems, improvements that would impact water and energy consumption as well (Walker et al. 2013). This work could provide a rich area of research in the integration of FEW systems, as all sectors may provide both sources and end-uses for heat.

In some cases, using waste to produce energy may trade off with or prevent nutrient recovery and reuse (e.g., biodigesters produce both energy and waste). The trade-offs between closing the loop for nutrients and energy should be examined carefully to provide a better understanding of how to optimize the integrated systems under a range of conditions (e.g., process technologies and scale; local demand for nutrients and energy; distance from waste production to treatment and then to end-users for energy and nutrients, recovery efficiencies, and waste characteristics).

iv) Closing the Water Loop

Water is perhaps the resource that lends itself most easily to the concept of closing the loop; the global water system itself is already a closed loop. Spatial disconnects in supply and demand (see Challenge 2) and differing qualities of water from potable, to wastewater, to saltwater, mean that efficiencies can be gained by considering the water loop on a variety of different scales. Minimizing the waste and runoff of water in urban and agricultural systems where water demand is high but supply is low can prevent or reduce the need to pump water long distances. Using a quality of water tailored to the specific use requirement (rather than simply depleting potable water stores for every task) can eliminate unnecessary treatment and pumping.

Innovative waste and water recycling projects are already underway in California. These projects can be scaled up and integrated into holistic FEW management. For example, the city of Los Angeles is investigating treating greywater -- which otherwise would be discharged into the ocean -- to potable standards, and providing incentives for residents to reuse graywater for lawn irrigation (LA Times Editorial Board 2015). In an urban center experiencing extreme drought with significant water supply imported hundreds of miles, retaining valuable water locally reduces pressures on both water and energy systems.

Capturing stormwater and managing runoff contamination will become increasingly important in urban and agricultural settings as demands increase and supply becomes more unpredictable. Stormwater management practices and green infrastructure technologies have been established to retain storm runoff in the local urban environment including, for example, rainwater harvesting (redirecting rainfall from rooftops to rain barrels or cisterns), rain gardens (using vegetated or mulched basins that collect rainwater runoff and allow it to infiltrate slowly or evaporate), and permeable landscaping (allowing water flow through what would more commonly be impermeable hardscape with porous asphalt, pervious concrete, interlocking pavers, etc.). The lessons learned and policies developed in the urban sphere can be used to inform and expedite management adaptations in agricultural contexts to prevent excessive runoff, encourage natural recharge, and promote water recycling. Engineered infiltration systems (Grebel et al. 2013), streambeds (Herzog et al. 2015; Robertson & Merkley 2009), and wetlands (Jasper et al. 2014) developed to control nutrient contamination in surface and groundwater bodies in urban settings can be evaluated for use in agricultural applications (Grebel et al. 2013; Herzog et al. 2015; Jasper et al. 2014). This stormwater can be stored seasonally in surface reservoirs or artificial wetlands, where it may be supplemented with recycled water. Currently, the management of stormwater and water supply resources by different institutions inhibits innovative uses of this water (Robertson & Merkley 2009).

Challenge 2: Resolving Spatiotemporal Disconnects in FEW Systems

Mismatches in time and space abound in FEW systems. Spatially, food is embedded with the water and energy necessary to produce and transport it to its final destination (e.g., consumer or disposal site), which in the U.S. averages 1500 miles from farmer to consumer (Pirog et al. 2001). Producing an average pound of beef requires approximately 1700 gallons of embedded water (Mekonnen et al. 2012) and 31 kWh of embedded energy (Alter 2010) (the average per capita daily energy consumption in the U.S., excluding embedded energy, is 30kWh) (U.S. Energy Information Administration 2015). In 2007, U.S. food production accounted for 2.4 billion kWh (Cuéllar & Weber 2010). Beyond the embedded water and energy in food, the spatial mismatch in food is characterized by a diverging demand and supply between, for example, urban and rural areas. As urbanization increases, products which traditionally were sold in local markets the same day they were harvested are now transported in longer, more complex supply chains (Parfitt et al. 2010). This trend is intensified by the fact that growing income tends to spark a dietary transition from a starched-based diet to more fresh fruits and vegetables, dairy, meat and fish – products with a short shelf life that require resource-intensive, chilled transportation (Parfitt et al. 2010). By extending the consumption phase of food, the cold chain can bridge the spatiotemporal disconnect in perishable food products and reduce food waste. However, though the cold chain addresses one challenge, it exacerbates others by increasing energy and water consumption. In addition, the cold chain is expected to grow in length and size as the population increases. Regionally rising temperatures caused by climate change will require more energy use to maintain the cold chain to mitigate the risk of food poisoning, food spoilage, and food waste (James & James 2010). For instance, energy use in the agricultural sector has been shown to increase in drought years by an average of 17.5%, partially as a result of higher energy needs to maintain the cold chain at proper temperatures (California Public Utilities Commission 2015).

Spatiotemporal disconnects in the energy and water sectors differ in frequency and complexity. Currently, daily electricity demand peaks, typically in the afternoon, are met with fossil fuel-based supplies. Many renewable energy sources, including solar and wind, provide an intermittent supply of energy based on available solar radiation or wind speed, respectively (Dyson et al. 2014). Grid operators, therefore, need baseload energy sources that can be easily turned on and off to meet demand requirements. As renewable energy generation increases, operators will have less control over the grid and new management strategies--such as battery storage or controls that turn selected energy-intensive equipment on and off--will be needed to match the demand to available supply.

For water, disconnects are primarily regional and seasonal, though daily patterns must also be considered. Historically, California's Sierra snowpack has naturally resolved seasonal disconnects and, with significant human intervention, alleviated spatial disconnects as well. As discussed in the Stressors section, climate change threatens the Sierra snowpack. Technical solutions are needed to replace the lost storage.

Water prices have increased dramatically due to drought. For example, in a Fresno-based Water District cost have increased from $140 per acre-foot in 2013 to $1100 in 2014 (Vekshin 2014). Increased water prices are having an economic impact on California's water-intensive agriculture and demonstrate the importance and relevance of implementing new solutions to minimize spatiotemporal disconnects. Resolving these disconnects is critical. For all FEW resources, having sufficient supply to meet demand at a local level is crucial to a healthy functioning society. Mitigating disconnects between FEW in space and time will require innovative storage systems for FEW and integrative policies and institutions.

i) Innovative FEW Storage

Optimized storage systems in cold chains are required at all stages of the supply chain, including in transportation systems, to reduce stress on energy and water systems. Efficiency in the cold chains is of particular importance, since it accounts for more than 1% of global CO_2 production (James & James 2010), and cold stores spend 60-70% of their electricity use on refrigeration (Evans et al. 2014a). Energy efficiency improvements for cold stores promise considerable cost savings: minor corrections and low-commitment changes like replacing door insulation or repairing evaporator fans result in considerable energy savings (ranging from 8% to 72%, and averaging around 28%) and have a rapid payback period (Evans et al. 2014b). Enclosing refrigerated areas in supermarkets provide a potential energy savings of 20-40% (Rewe Sustainability Report 2012). Alternative refrigeration systems (e.g. Trigeneration, Air Cycle, Sorption-Adsorption Systems, Thermoelectric, Stirling Cycle, Thermoacoustic and Magnetic refrigeration) offer considerable energy savings as well (James & James 2010).

Water and energy storage are inextricably linked. Whenever water is stored, whether above- or below-ground, it can consume or generate energy as it is removed from storage. While traditional energy storage systems (i.e., batteries) may be feasible on the scale required for renewable energies, they contain materials with negative environmental impacts caused, for example, by the heavy metals used to manufacture them. The associated impacts on public health and environment from the mining, use, and disposal of such materials should be carefully assessed and considered in comparing storage options.

Increasingly, pumped surface storage is being considered as a "battery," an efficient and cost-effective way to balance electricity supply and demand and to reduce greenhouse gas emissions (Poonpun & Jewell 2008). Globally, pumped hydropower accounts for 98% of installed storage capacity (Roach 2015). New large-scale pumped surface storage projects are planned for California, though these projects are criticized for their overall higher, albeit cleaner, use of electricity and environmental impacts (e.g., habitat loss due to initial flooding, effects of rapid water-level fluctuations). Small-scale hydropower technologies have the potential to provide this service on a more distributed scale with fewer negative environmental effects. For example, in-line turbines can be installed in urban or agricultural supply and in urban or rural distribution pipes to capture excess energy in the system; further, underwater balloons may provide a new way to store energy as compressed air within natural and man-made reservoirs (Nield 2015).

As precipitation patterns change in California, it will be increasingly necessary to store more water seasonally to replace lost snowpack or, longer term, as a drought reserve. This water will be needed in order to support agricultural, urban, and other needs, regardless of whether the energy can be recovered. On farms, better soil management techniques (e.g., no-till agriculture) can preserve more green water in the upper soil layers and avoid additional irrigation in the dry season (Liu et al. 2013). When irrigation is necessary, it can be managed efficiently using remote sensing and other sensor-based technologies to determine when and how much water should be used (Ali 2011). Irrigation systems can be more intelligently controlled so that pump equipment operates when excess electricity is available during high renewable generation periods. Irrigation decisions, however, should be informed by an integrated, region-specific analysis that recognizes that irrigation water conservation may negatively impact the environment in cases where the local hydrology has come to depend on the excess water (Ward & Pullido-Velaquez 2008). Stormwater approaches, discussed in Challenge 1, may also address this issue.

Alternately, water can be stored underground as a long-term reserve for droughts. Several methods for managing aquifer recharge are available, including locating and enhancing natural recharge zones, increasing permeable surfaces in urban areas, pumping water into aquifers, or flooding fields on agricultural lands when hydrology and crops are favorable (Johnson 2015). Techniques developed for the oil and gas industry may allow us to increase groundwater storage capacity in aquifers and reclaim capacity lost to subsidence. If capacity at shallow depths is expanded, these "frackquifers" could reduce the energy impacts of pumping water in and out of underground storage. If "frackquifers" could be created to store recycled water for indirect reuse to meet for 1% of California's 2010 groundwater demand 300 feet above existing water levels, 16,000 MWh of pumping could be avoided annually, enough to power 2,200 California households (USGS 2014, CPUC 2010, US Energy Information Administration 2009). Fracking in the oil and gas industry is controversial. Some risks associated with it may extend to “frackquifers” (e.g., high traffic, local contamination, triggering small earthquakes). Research into relative risks and benefits is needed before implementation is considered.

ii) Integrating policies and institutions

The extensive interconnectivity of FEW systems means that integrated policies and institutions are needed in order to deal efficiently with the challenges identified above. Unfortunately, collaboration among, and even within, respective FEW actors is rare. Urban water systems are highly disaggregated, with different institutions managing each component of the system without due consideration of the effects on other components. Ideally, water management would be horizontally integrated for potable water supply, non-potable water supply, wastewater, and stormwater, as well as the affected hydrologic resources, to enable more efficient and sustainable planning.

There have been successes: UC Davis and the EPA Office of Research and Development, organizations that focus on biogas management technologies for different biogas applications, recently pledged more collaborative effort (Kosusko 2015). Nonetheless, building interconnectivity within and among FEW systems is a daunting task. Institutional inertia, resistance to change, and continued thinking only in terms of one’s own institution inhibit collaboration with multiple stakeholders (e.g., communities, agencies, civil society and the private sector) and slow, if not prevent, innovation (Ringler et al 2013; Kiparsky et al. 2013).

U.S. policymaking processes also require integration since FEW regulators operate with separate funding, accounting mechanisms, governmental oversight, and legislative bodies. It will be necessary to connect food management, water planning, and energy production to develop synergies across both areas and across multiple institutions such as the Department of the Energy, Environmental Protection Agency, the US Geological Society, and the US Department of Agriculture (e.g., Webber 2008). Collaboration among all FEW policy-makers would increase the understanding of system interdependencies and shared or competing resource needs, and thus limit policies focused on one area from negatively affecting others.

Integrating policies and institutions is also crucial as increased interconnectivity promotes efficiency and decreases resource intensity. When the Danish city of Kalundborg developed an integrative industrial park, it found that increased collaboration among companies and state actors yielded numerous environmental benefits (e.g., increased CO_2 savings, reduced waste water production, and decreased demand for pumped groundwater) through exchanges of energy, reuse of waste products, and use of recycled water (Jacobsen 2006).

Other factors exacerbate the institutional challenges in FEW. Temporal disconnects exist between project development, policy changes, and environmental effects; policy changes are often outpaced by the increasing dynamics of development (SEI 2011). Moreover, there is a mismatch between existing institutional knowledge and the adoption of developed technologies. To address these issues collectively, we need more agile and flexible institutions that work horizontally across industries and apply tailored information (SEI 2011).

Challenge 3: Creating Actionable Information

The FEW nexus involves three complex systems with a variety of actors ranging from producers and consumers to researchers and policy-makers. These stakeholders' FEW-related actions are impacted by data, information, and knowledge across a diverse array of topics, including regulatory regimes, access to markets and technology, economic benefits, and socio-cultural factors. Further, different stakeholders have varying perspectives on what information is valuable and legitimate (Cook et al. 2013). Moving toward integrated FEW systems will require accurate representation of values and perspectives of different stakeholders from multiple disciplines. For complex problems like those within the FEW nexus, interdisciplinary perspectives on social, cultural, and political elements of the problems are necessary in order to identify, implement, and achieve effective solutions (Cooke & Vermaire 2015; Kirchhoff et al. 2013).

This section focuses on three aspects of actionable information: (i) collecting integrated FEW data using cyber-physical systems and life-cycle assessment frameworks; (ii) translating knowledge and information that is useful to and usable by different user groups and (iii) informing decision-makers and influencing policy by communicating with producers and consumers of FEW about efficient choices and effective actions.

(i) Collecting integrated food, energy, and water data

Currently, there is insufficient data on the production and consumption of FEW resources both nationally and regionally (Lundy et al. 2014). Cyber physical systems (CPS) integrate computation, networking, and physical processes, using embedded computers and networks to monitor and control physical processes with feedback loops where physical processes affect computations and vice versa (Asare et al. 2012). CPS can collect data on energy, water, food, and/or environmental impacts to develop a baseline for current FEW resource use (Lundy et al. 2014).

Within FEW systems, CPS has increased both knowledge (through remote and wireless sensors) and control (through electronic manipulation of instrumentation). Precision agriculture uses CPS to make detailed environmental observations and subsequently perform high-precision resource management to increase water, fertilizer, and herbicide efficiency (Gebbers & Adamchuk 2010). For example, sensor-based nitrogen management systems for grain production have been shown to increase nitrogen use efficiency by up to 368% and to reduce residual nitrogen in the soil by 30-50% with no reduction in yield (Diacono et al. 2013). In the energy sector, large utility providers have installed smart electricity meters across their service territories. These large smart grids provide detailed consumer information and allow for consumption-driven resource management. For example, Pacific Gas & Electric in Northern California uses a smart meter network to calculate rate incentives to curtail customers' power usage on peak days (Lai et al. 2011). Within the water sector, remote floating sensors are being developed to be released into rivers, providing unprecedented detailed information about water flows which can inform regional water-management plans (Rabbani et al. 2009). Energy and water quality management software for water utilities can work with supervisory control and data acquisition systems to balance energy costs and water quality requirements and, with additional research, may be able to respond to energy supply and demand signals and evaluate energy-related GHG emissions in real time (Cherchi et al. 2015).

The cross-sectoral impacts of FEW systems across the environmental, economic, and social realms are integral to the management of the nexus (Azapagic 2015). In addition to collecting data on each individual resource, a complete understanding of the FEW nexus requires identification of relationships among the different systems. Life-cycle assessment (LCA) can evaluate these relationships by estimating the energy intensity of food and water production, and the water intensity of both food and energy production (Jeswani et al. 2015).

LCA is a rigorous, quantitative method for tracking inputs, byproducts, and waste of a product, process, or system over its lifecycle from material procurement to disposal (ISO 2010; Curran 1996). LCA elucidates environmental tradeoffs, helps avoid unintended consequences, and reveals interconnections in the FEW nexus by evaluating the supply chain of each resource, integrating the siloed data of each sector (Jeswani et al. 2015; Al-Ansari et al. 2014). Since LCA track energy and water through supply chains, LCAs can be used to make FEW systems more resilient and sustainable by identifying inefficiencies, synergies, or other improvements that need to be made to the system. LCA is particularly useful when making management decisions about the costs and benefits of a particular strategy and quantifying the tradeoffs required between one strategy and another. FEW-related choices that could be informed by LCA include comparing above- and below-ground water storage under different hydrological conditions, including their potential energy use and/or generation; evaluating the impacts of cold-chain dependence for particular products; weighing tradeoffs between water, nutrient, and energy recovery; identifying appropriate scales and treatment technologies for decentralized and on-farm waste management and water reuse; and comparing agroecology vs. conventional farming practices.

(ii) Translating information

Collecting data using CPS and LCA alone will not be sufficient to drive sustainable solutions within FEW systems. Studies have shown that scientific findings in themselves do not necessarily result in pro-environmental behavior. Cooke and Vermaire (2015) cite a growing number of highprofile examples in which environmental science and technology alone have failed to deliver effective solutions. Though the last decade has seen many scientific and technological advances, the rate of use of scientific knowledge in environmental decision-making has been low (Kirchhoff et al. 2013). Information and data alone do not ensure action will be taken. For example, within food systems, much analysis has focused on inputs to agricultural systems (e.g., fertilizer, land-use), and used observations of these as a proxy for their impact. This creates “islands of knowledge in a sea of ignorance” -- we have detailed knowledge about narrow aspects of broad and complex systems while remaining ignorant of their impacts and interactions (Meinke et al. 2008).

Increasingly, scientists are calling for translation of science into usable and actionable information (Meinke et al. 2008; Dilling & Lemos 2011). Since different actors perceive the usefulness of information differently (Dilling & Lemos 2011), communications should be tailored to the specific user-group, for example, by incorporating multiple formats such as online resources, print media, visuals, and grassroots educational campaigns. Three examples of translation or increasing the usability of information are described below:

Co-production of knowledge with researchers, policy-makers and practitioners. Willingness to accept and use information can improve when stakeholders obtain, receive and participate in its production (Lemos et al. 2012). Co-production of information by scientists, policy-makers, and practitioners results in more robust assessments than isolated information provision (Weichselgartner and Kasperson 2010). Pohl et al. (2010) show how co-production of environmental knowledge can lead to increased uptake of sustainable action using case studies. For example, in their drought management case study in Kenya, co-production enabled researchers to understand the relevance of farmers’ local knowledge and the farmers to understand the importance of new scientific findings. This eventually led to increased mutual understanding of various drought management options. Implementing co-production of information in FEW systems (e.g., the use of CPS to gain detailed information about agricultural practices on specific farms) will likely provide more useful information and may be beneficial to all stakeholders.

Increasing interactions with stakeholders. Increased interaction among users can reduce barriers to information use (Lemos et al. 2012). For example, producer-user workshops between water scientists and water managers in the Western U.S. helped water managers understand how stream flows are reconstructed from tree rings and why this information is relevant for long-term drought planning (Kirchhoff et al. 2013).

Creating value-added information. Information is more useful when value is added to existing information to better meet users' needs. This is often done by transforming informational knowledge to operational or decision-oriented knowledge (Lemos et al. 2012). An example of this is what type of weather information is provided to farmers. Weather or climate information is more useful for farmers' decision-making when combined with crop insurance data or potential planting- or harvesting-related adaptations. Data visualization can also facilitate usability and has been used to aid local decision-making across a range of sectors, including sustainable forest management, climate impacts, and landscape changes (Kirchhoff et al. 2013).

(iii) Informing decision-makers and influencing their behavior

FEW decision-makers are diverse, encompassing producers such as farmers, water utilities, energy generating companies, and retailers, along with consumers of FEW. All stakeholders influence the structure of FEW systems: from producers' and distributors' technology use and management practices to consumers' expectations and willingness to purchase products and services (SEI 2011). Stakeholders' decisions depend on information about complex, interconnected factors such as markets, technology, regulations, economics, politics, society, culture, health, safety, and the environment. Therefore, beyond creating actionable information, how information is communicated to decision-makers can influence the sustainability of FEW decisions and behavior.

Effectively informing decision-makers of FEW challenges and opportunities requires a "behavior-centric" approach (Vlek & Steg 2007). Enduring solutions to environmental problems are not possible without considering the different perceptions, knowledge, and needs of stakeholders. Solution mechanisms that integrate behavior and technology result in better outcomes than siloed approaches. Environmental impacts of efficient FEW technology will depend on actual user behavior which can be shaped, enhanced, or constrained by specific features of the technical environment -- for example, new, energy-efficient light bulbs contain traces of mercury, necessitating a trade-off by the consumer prior to adoption (Midden et al. 2007).

In addition to informing decision-makers, information must aim to influence policy, requiring effective communication of information to policy-makers in the public sector, the private sector, and civil society institutions working at the FEW interface (SEI 2011). Not only is communication important, but the framing of pertinent information is key. If relevant information or policy choices are communicated and framed in ways that cannot garner political and public support, they may fail to enter the arena of policy debate or decision-making (Vogel et al. 2007).

Some effective ways of informing decision-makers and influencing their behavior are:

Technologies for increasing awareness. Information and communication technologies (ICT) are often perceived to be critical in the shift towards a knowledge-based society (Lim & Barnes 2002). ICT has many applications in environmental informatics (Hilty et al. 2011). Communicating FEW information can be supported by database systems, geographic information systems, modeling and simulations, knowledge-based systems, and neural networks. For example, Next Drop, a start-up venture in Bangalore, India, uses real-time data and SMS-based messaging to inform water users with intermittent supply when they will next be receiving water (Welle et al. 2015). This ICT initiative connects the water-managing utility to customers to enable the widespread dissemination of water availability data. Further, mass media can communicate and disseminate information to a larger audience as well as to encourage stakeholder interest in sustainability issues. Jacobs et al. (2005) suggest that cultivating relationships with local press and broadcasters can help improve the likelihood of successful knowledge transfer. ICT experts, such as ones in the UC Berkeley School of Information, can help design and promote novel information communication methods to aid in disseminating FEW information effectively to larger audiences.

Labelling. Communicating the socio-ecological performance of various products with better labelling can promote sustainability in current patterns of consumption and production (Bratt et al. 2013). For instance, energy labels for various household appliances enable consumers to make more efficient decisions. A recent study on China's Energy Efficiency Label suggests that this label has positively influenced consumer decisions about purchasing air conditioners and refrigerators in Shanghai (Shen & Saijo 2009). Lawrence Berkeley National Lab's Environmental Energy Technologies Division has an "Energy Efficiency Standards Group" that analyzes technical, economic, and environmental aspects of more efficient appliances and equipment. Expertise like theirs can be used to improve labelling in other FEW systems as well.

Education. Environmental and sustainability challenges have important connections to and implications for education and schooling (Rickinson 2001). Environmental education is spreading in national educational policies and curricula with the aim of educating a generation of students who are knowledgeable about environmental problems and potential solutions (Pooley & O'Connor 2000). Outdoor ecology education has been shown to change long-term environmental perspectives and motivate students to make responsible environmental decisions through a combination of first-hand experience and participatory interaction (Bogner 1998). Environmental and sustainability education for all ages is therefore critical to sustain long-term behavioral change among producers and consumers of FEW systems.

Boundary Organizations. These organizations link the worlds of science and practice (Vogel et al. 2007), facilitating communication between scientists and decision-makers or policy developers, particularly with respect to complex environmental problems (Cook et al. 2013). In FEW systems, cooperative extension programs in the U.S. are one example of a boundary organization working at the interface of science, policy, and practice. Typically housed in land grant universities, Cooperative Extensions engage large networks of practitioner-educators who interact with local stakeholders and decision makers within FEW systems on a regular basis (Feldman & Ingram 2009). Cooperative extension programs could provide the necessary trainings and capacity building to speed the adoption of innovative FEW practices.

Conclusion

The FEW system trilemmas in drought-prone, semi-arid regions are particularly acute and likely to worsen. As highlighted above, this is due to the multiplicative and interacting system stressors including climate variability, persistent waste, continued pollution, and shifting demographics in these regions. We have identified and proposed solution mechanisms for three research challenges: (i) closing the loop across FEW systems; (ii) resolving spatiotemporal disconnects in FEW; and (ii) creating actionable information. The integrative solution mechanisms we propose focus on information and data, developing appropriate technologies, and incentivizing behavior change to provide concrete direction for innovative research that will lessen, prevent, and resolve trilemmas that are likely to arise when integrating the management of FEW systems.

We contend that fully understanding and ultimately managing FEW systems will require a combination of (i) discovery-driven disciplinary science in various subareas of FEW systems; (ii) research that integrates advances in FEW science to resolve trilemmas ; and (iii) the training and formation of interdisciplinary teams. The development and implementation of novel solutions to FEW trilemmas will flow from disciplinary science through to integrated, interdisciplinary management and policy. Discoveries in disciplinary science are the precursors to the development of technologies and policies. Through our explication of FEW challenges, we have provided examples of the need for basic research relevant to FEW systems. These include for example, a deeper and more fundamental understanding of the partitioning and use of water in plants and soil as well as advances in contaminant detection and remediation for wastewater reuse.

While disciplinary discoveries create new knowledge and open new pathways to resolve FEW trilemmas, there are inherently physical, natural and social science components in the intersection of FEW systems. Thus, resolving FEW trilemmas requires the transfer and integration of knowledge from disparate disciplines. Closing the loop by reusing waste across FEW is a good example; nutrients can be recovered from food and water waste, providing cross-system resources and minimizing waste.

Solutions at the FEW nexus will require combining knowledge from different disciplines; the need for interdisciplinary teams is clear. Not only are scientists from different disciplines key to this process, but so are decision and policy makers. Bringing scientists together with practitioners can be efficient for science and effective for management (Dilling & Lemos 2011). The scientists can highlight what is possible, probable, and impossible from a science and technology standpoint, while the practitioners can highlight the hard and soft constraints as well as suggest new avenues for exploration. For example, while distributed waste remediation facilities can resolve many transport issues, the cost of these facilities can be prohibitive to small farms. The challenge is putting these teams together is the group learning to speak the same language. Science, universities, and the public are becoming increasingly accepting and interested in interdisciplinarity, the acceptance of interdisciplinarity scholarship still has a ways to go in the broader academic community especially, for early or mid-career researchers (Rhoten & Parker 2004).

References

Al-Ansari, Tareq, Anna Korre, Zhenggang Nie, and Nilay Shah. 2014. “Development of a Life Cycle Assessment Model for the Analysis of the Energy, Water and Food Nexus.” In *Computer Aided Chemical Engineering*, 33:1039–44. Elsevier. http://linkinghub.elsevier.com/retrieve/pii/B9780444634559500088.

Albanese, S., and D. Cicchella. 2012. “Legacy Problems in Urban Geochemistry.” *Elements* 8 (6): 423–28. doi:10.2113/gselements.8.6.423.

Ali, M. H. 2011. *Practices of Irrigation & On-Farm Water Management: Volume 2*. New York, NY: Springer New York. http://link.springer.com/10.1007/978-1-4419-7637-6.

Alter. 2010. “Energy Required To Produce a Pound of Food.” *TreeHugger*. http://www.treehugger.com/green-food/energy-required-to-produce-a-pound-of-food.html.

Asare Philip, University of Virginia, David Broman, UC Berkeley, Edward A. Lee, UC Berkeley, Martin Torngren, KTH, and S. Shyam Sunder, NIST. 2012. “Cyber-Physical Systems - a Concept Map.” http://cyberphysicalsystems.org/.

Azapagic, Adisa. 2015. “Special Issue: Sustainability Issues in the Food–energy–water Nexus.” *Sustainable Production and Consumption* 2 (April): 1–2. doi:10.1016/j.spc.2015.08.002.

Belmecheri, Soumaya, Flurin Babst, Eugene R. Wahl, David W. Stahle, and Valerie Trouet. 2015. “Multi-Century Evaluation of Sierra Nevada Snowpack.” *Nature Climate Change*, September. doi:10.1038/nclimate2809.

Bogner, Franz X. 1998. “The Influence of Short-Term Outdoor Ecology Education on Long-Term Variables of Environmental Perspective.” *The Journal of Environmental Education* 29 (4): 17–29. doi:10.1080/00958969809599124.

Bratt, Cecilia, Sophie Hallstedt, K.-H. Robèrt, Göran Broman, and Jonas Oldmark. 2013. “Assessment of Criteria Development for Public Procurement from a Strategic Sustainability Perspective.” *Journal of Cleaner Production* 52 (August): 309–16. doi:10.1016/j.jclepro.2013.02.007.

Buzby, Jean C., Hodan F. Wells, and Jeffrey Hyman. 2014. “The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States.” Number 121. Economic Information Bulletin. USDA. http://www.ers.usda.gov/media/1282296/eib121.pdf.

California Department of Water Resources (DWR). (2015). DWR Bulletin 120. California Cooperative Snow Surveys.

Carlton, J. (2015, February 27). California Farmers Face Another Year Without Federal Water. The Wall Street Journal.

Chakrabarti, Alicia R., John M. Hake, Donald M.D. Gray, Vincent P. De Lange, and Edward H. McCormick. 2011a. “EBMUD’s Journey to Becoming a Net Electricity Producer.”

Proceedings of the Water Environment Federation 2011 (6): 625–33. doi:10.2175/193864711802836634.

Chakrabarti, Alicia R., John M. Hake, Vincent P. De Lange, and Edward H. McCormick. 2011b. “A Case Study of a Large Wastewater Treatment Plant Demonstrating an Integrated Approach to Climate Change.” *Proceedings of the Water Environment Federation* 2011 (6): 1172–80. doi:10.2175/193864711802836788.

Cherchi, Carla, Mohammad Badruzzaman, Joan Oppenheimer, Christopher M. Bros, and Joseph G. Jacangelo. 2015. “Energy and Water Quality Management Systems for Water Utility’s Operations: A Review.” *Journal of Environmental Management* 153 (April): 108–20. doi:10.1016/j.jenvman.2015.01.051.

Coleman-Jensen, A., Gregory, C., & Singh, A. (2014). Household food security in the United States in 2013. Economic Research Report.

Cook, Carly N., Michael B. Mascia, Mark W. Schwartz, Hugh P. Possingham, and Richard A. Fuller. 2013. “Achieving Conservation Science That Bridges the Knowledge-Action Boundary: Achieving Effective Conservation Science.” *Conservation Biology* 27 (4): 669–78. doi:10.1111/cobi.12050.

Cooke, Steven J., and JesseC. Vermaire. 2015. “Environmental Studies and Environmental Science Today: Inevitable Mission Creep and Integration in Action-Oriented Transdisciplinary Areas of Inquiry, Training and Practice.” *Journal of Environmental Studies and Sciences* 5 (1): 70–78. doi:10.1007/s13412-014-0220-x.

Cuéllar, Amanda D., and Michael E. Webber. 2010. “Wasted Food, Wasted Energy: The Embedded Energy in Food Waste in the United States.” *Environmental Science & Technology* 44 (16): 6464–69. doi:10.1021/es100310d.

Curran, Mary Ann. 1996. “Environmental Life-Cycle Assessment.” *The International Journal of Life Cycle Assessment* 1 (3): 179–179. doi:10.1007/BF02978949.

Daigger, Glen T. 2009. “Evolving Urban Water and Residuals Management Paradigms: Water Reclamation and Reuse, Decentralization, and Resource Recovery.” *Water Environment Research* 81 (8): 809–23. doi:10.2175/106143009X425898.

Desloover, Joachim, Andualem Abate Woldeyohannis, Willy Verstraete, Nico Boon, and Korneel Rabaey. 2012. “Electrochemical Resource Recovery from Digestate to Prevent Ammonia Toxicity during Anaerobic Digestion.” *Environmental Science & Technology* 46 (21): 12209–16. doi:10.1021/es3028154.

Diacono, M., Rubino, P., & Montemurro, F. (2013). Precision nitrogen management of wheat. A review. Agronomy for Sustainable Development. doi:10.1007/s13593-012-0111-z

Diffenbaugh, Noah S., Daniel L. Swain, and Danielle Touma. 2015. “Anthropogenic Warming Has Increased Drought Risk in California.” *Proceedings of the National Academy of Sciences* 112 (13): 3931–36. doi:10.1073/pnas.1422385112.

Dilling, Lisa, and Maria Carmen Lemos. 2011. "Creating Usable Science: Opportunities and Constraints for Climate Knowledge Use and Their Implications for Science Policy." *Global Environmental Change* 21 (2): 680–89. doi:10.1016/j.gloenvcha.2010.11.006.

Dyson, Mark E.H., Samuel D. Borgeson, Michaelangelo D. Tabone, and Duncan S. Callaway. 2014. "Using Smart Meter Data to Estimate Demand Response Potential, with Application to Solar Energy Integration." *Energy Policy* 73 (October): 607–19. doi:10.1016/j.enpol.2014.05.053.

Evans, J.A., A.M. Foster, J.-M. Huet, L. Reinholdt, K. Fikiin, C. Zilio, M. Houska, et al. 2014a. "Specific Energy Consumption Values for Various Refrigerated Food Cold Stores." *Energy and Buildings* 74 (May): 141–51. doi:10.1016/j.enbuild.2013.11.075.

Evans, J.A., E.C. Hammond, A.J. Gigiel, A.M. Fostera, L. Reinholdt, K. Fikiin, and C. Zilio. 2014b. "Assessment of Methods to Reduce the Energy Consumption of Food Cold Stores." *Applied Thermal Engineering* 62 (2): 697–705. doi:10.1016/j.applthermaleng.2013.10.023.

Feldman, David L., and Helen M. Ingram. 2009. "Making Science Useful to Decision Makers: Climate Forecasts, Water Management, and Knowledge Networks." *Weather, Climate, and Society* 1 (1): 9–21. doi:10.1175/2009WCAS1007.1.

Fulton, J., & Cooley, H. (2015). The water footprint of California's energy system, 1990-2012. Environmental Science & Technology, 49(6), 3314–21. doi:10.1021/es505034x

Gebbers, R., & Adamchuk, V. I. (2010). Precision agriculture and food security. Science (New York, N.Y.), 327(5967), 828–831. doi:10.1126/science.1183899

Gerland, P., A. E. Raftery, H. ev ikova, N. Li, D. Gu, T. Spoorenberg, L. Alkema, et al. 2014. "World Population Stabilization Unlikely This Century." *Science* 346 (6206): 234–37. doi:10.1126/science.1257469.

Gewald, Daniela, Konstantinos Siokos, Sotirios Karellas, and Hartmut Spliethoff. 2012. "Waste Heat Recovery from a Landfill Gas-Fired Power Plant." *Renewable and Sustainable Energy Reviews* 16 (4): 1779–89. doi:10.1016/j.rser.2012.01.036.

Gleick, P. H. (2015). Impacts of California's Ongoing Drought: Hydroelectricity Generation. Oakland, CA.

Grantham, Theodore E, and Joshua H Viers. 2014. "100 Years of California's Water Rights System: Patterns, Trends and Uncertainty." *Environmental Research Letters* 9 (8): 084012. doi:10.1088/1748-9326/9/8/084012.

Grebel, Janel E., Sanjay K. Mohanty, Andrew A. Torkelson, Alexandria B. Boehm, Christopher P. Higgins, Reed M. Maxwell, Kara L. Nelson, and David L. Sedlak. 2013. "Engineered Infiltration Systems for Urban Stormwater Reclamation." *Environmental Engineering Science* 30 (8): 437–54. doi:10.1089/ees.2012.0312.

Griffin, D., & Anchukaitis, K. J. (2014). How unusual is the 2012-2014 California drought? Geophysical Research Letters, 41(24), 9017–9023. doi:10.1002/2014GL062433

Hall, Clare, and Felipe Osses. 2013. “A Review to Inform Understanding of the Use of Food Safety Messages on Food Labels: Use of Food Safety Messages on Food Labels.” *International Journal of Consumer Studies* 37 (4): 422–32. doi:10.1111/ijcs.12010.

Hall, Kevin D., Juen Guo, Michael Dore, and Carson C. Chow. 2009. “The Progressive Increase of Food Waste in America and Its Environmental Impact.” Edited by Thorkild I. A. Sorensen. *PLoS ONE* 4 (11): e7940. doi:10.1371/journal.pone.0007940.

Hanak, Ellen, ed. 2011. *Managing California’s Water: From Conflict to Reconciliation*. San Francisco, CA: Public Policy Institute of California.

Herzog, S. P., C. P. Higgins, and J. E. McCray. 2015. “Engineered Streambeds for Induced Hyporheic Flow: Enhanced Removal of Nutrients, Pathogens, and Metals from Urban Streams.” *Journal of Environmental Engineering*, August, 04015053. doi:10.1061/(ASCE)EE.1943-7870.0001012.

Howitt Richard, Duncan MacEwan, Josué Medellín-Azuara, Jay Lund, and Daniel Sumner. 2015. “Economic Analysis of the 2015 Drought For California Agriculture.” In . UC Davis Center for Watershed Sciences ERA Economics UC Agricultural Issues Center.

ISO. 2010. “ISO 14040:2006 - Environmental Management -- Life Cycle Assessment -- Principles and Framework.” http://www.iso.org/iso/catalogue_detail?csnumber=37456.

Jacobs, Katharine, Gregg Garfin, and Melanie Lenart. 2005. “More than Just Talk: Connecting Science and Decisionmaking.” *Environment: Science and Policy for Sustainable Development* 47 (9): 6–21. doi:10.3200/ENVT.47.9.6-21.

Jacobsen, Noel Brings. 2008. “Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and Environmental Aspects.” *Journal of Industrial Ecology* 10 (1-2): 239–55. doi:10.1162/108819806775545411.

Jacobson, Mark Z., Mark A. Delucchi, Mary A. Cameron, and Bethany A. Frew. 2015. “Low-Cost Solution to the Grid Reliability Problem with 100% Penetration of Intermittent Wind, Water, and Solar for All Purposes.” *Proceedings of the National Academy of Sciences* 112 (49): 15060–65. doi:10.1073/pnas.1510028112.

James, S.J., and C. James. 2010. “The Food Cold-Chain and Climate Change.” *Food Research International* 43 (7): 1944–56. doi:10.1016/j.foodres.2010.02.001.

Jasper, Justin T., Zackary L. Jones, Jonathan O. Sharp, and David L. Sedlak. 2014. “Nitrate Removal in Shallow, Open-Water Treatment Wetlands.” *Environmental Science & Technology* 48 (19): 11512–20. doi:10.1021/es502785t.

Jeswani, Harish Kumar, Richard Burkinshaw, and Adisa Azapagic. 2015. “Environmental Sustainability Issues in the Food–energy–water Nexus: Breakfast Cereals and Snacks.” *Sustainable Production and Consumption* 2 (April): 17–28. doi:10.1016/j.spc.2015.08.001.

Johnson, Nathanael. 2015. “How California Could Get Smarter about Droughts and Flooding.” *LockerDome*. September 11. http://grist.org/food/how-california-could-get-smarter-about-droughts-and-flooding/?utm_medium=email&utm_source=newsletter&utm_campaign=daily-horizon.

Kiparsky, Michael. 2013. "The Innovation Deficit in Urban Water: The Need for an Integrated Perspective on Institutions, Organizations, and Technology." 30.8. Environmental Engineering Science.

Kirchhoff, Christine J., Maria Carmen Lemos, and Suraje Dessai. 2013. "Actionable Knowledge for Environmental Decision Making: Broadening the Usability of Climate Science." *Annual Review of Environment and Resources* 38 (1): 393–414. doi:10.1146/annurev-environ-022112-112828.

Kizito, Simon, Shubiao Wu, W. Kipkemoi Kirui, Ming Lei, Qimin Lu, Hamidou Bah, and Renjie Dong. 2015. "Evaluation of Slow Pyrolyzed Wood and Rice Husks Biochar for Adsorption of Ammonium Nitrogen from Piggery Manure Anaerobic Digestate Slurry." *Science of The Total Environment* 505 (February): 102–12. doi:10.1016/j.scitotenv.2014.09.096.

Kosusko Michael, EPA ORD, and Robert B. Williams, California Biogas Collaborative (CBC), UC Davis Laura C. Moreno, UC Berkeley Charlotte C. Ely, EPA Region 9. 2015. "An Approach to Compare the Air Quality, Climate and Economic Impacts of Biogas Management Technologies." &WMA ACE 2015: National Risk Management Research Laboratory, Air Pollution Prevention and Control Division.

Knobeloch, L., Salna, B., Hogan, A., Postle, J., & Anderson, H. 2000. "Blue Babies and Nitrate-Contaminated Well Water." Environmental Health Perspectives.

LA Times Editorial Board. 2015. "Drought Provides Opportunity for L.A. to Get Gray Water Right." *Latimes.com*. http://www.latimes.com/opinion/editorials/la-ed-gray-water-20150420-story.html.

Lai, Judy, Nicholas DeForest, Sila Kiliccote, Michael Stadler, Chris Marnay, and Jon Donadee. 2011. "Evaluation of Evolving Residential Electricity Tariffs." Lawrence Berkeley National Laboratory, Carnegie Mellon University.

Larsen, Tove A., Alfredo C. Alder, Rik I. L. Eggen, Max Maurer, and Judit Lienert. 2009. "Source Separation: Will We See a Paradigm Shift in Wastewater Handling? [1]." *Environmental Science & Technology* 43 (16): 6121–25. doi:10.1021/es803001r.

Law, Richard, Adam Harvey, and David Reay. 2013. "Opportunities for Low-Grade Heat Recovery in the UK Food Processing Industry." *Applied Thermal Engineering* 53 (2): 188–96. doi:10.1016/j.applthermaleng.2012.03.024.

Lemos, Maria Carmen, Christine J. Kirchhoff, and Vijay Ramprasad. 2012. "Narrowing the Climate Information Usability Gap." *Nature Climate Change* 2 (11): 789–94. doi:10.1038/nclimate1614.

Lim, Cher Ping, and Sally Barnes. 2002. "'Those Who Can, Teach' - The Pivotal Role of the Teacher in the Information and Communication Technologies (ICT) Learning

Environment.” *Journal of Educational Media* 27 (1-2): 19–40. doi:10.1080/1358165020270103.

Liu, Shuang, Xing-Yi Zhang, Jingyi Yang, and Craig F. Drury. 2013. “Effect of Conservation and Conventional Tillage on Soil Water Storage, Water Use Efficiency and Productivity of Corn and Soybean in Northeast China.” *Acta Agriculturae Scandinavica, Section B - Soil & Plant Science* 63 (5): 383–94. doi:10.1080/09064710.2012.762803.

Lumley, Nicholas P.G., Dotti F. Ramey, Ana L. Prieto, Robert J. Braun, Tzahi Y. Cath, and Jason M. Porter. 2014. “Techno-Economic Analysis of Wastewater Sludge Gasification: A Decentralized Urban Perspective.” *Bioresource Technology* 161 (June): 385–94. doi:10.1016/j.biortech.2014.03.040.

Lundy, Jeff, and Lawrence Bowdish. 2014. “The Energy-Water-Food Nexus.” U.S. Chamber of commerce foundation.

Lono-Batura Maile, Yinan Qi and Ned Beecher. 2015. “Biogas Production And Potential From U.S. Wastewater Treatment « « BioCycle BioCycle.” Vol. 53, No. 12,. BioCycle. 2012. Accessed December 10. http://www.biocycle.net/2012/12/18/biogas-production-and-potential-from-u-s-wastewater-treatment/.

Marin Carbon Project. 2008. “Marin Carbon Project.” http://www.marincarbonproject.org/.

Markham. 2015. “Home-Sized Biogas Unit Turns Organic Waste into Cooking Fuel and Fertilizer, for under $900.” *TreeHugger*. http://www.treehugger.com/clean-technology/home-sized-biogas-unit-turns-organic-waste-cooking-fuel-and-fertilizer-under-900.html.

McEwan, D., Tynan, T. J., & Wilson, L. K. (2014). Management of the California State Water Project. Bulletin 132-12 - California, Department of Water Resources.

Meinke, H, R Nelson, P Kokic, R Stone, R Selvaraju, and W Baethgen. 2006. “Actionable Climate Knowledge: From Analysis to Synthesis.” *Climate Research* 33 (December): 101–10. doi:10.3354/cr033101.

Mekonnen, Mesfin M., and Arjen Y. Hoekstra. 2012. “A Global Assessment of the Water Footprint of Farm Animal Products.” *Ecosystems* 15 (3): 401–15. doi:10.1007/s10021-011-9517-8.

Midden, Cees J. H., Florian G. Kaiser, and L. Teddy McCalley. 2007. “Technology’s Four Roles in Understanding Individuals’ Conservation of Natural Resources.” *Journal of Social Issues* 63 (1): 155–74. doi:10.1111/j.1540-4560.2007.00501.x.

Nield, David. 2015. “Underwater Balloons Could Give Us a New Way of Storing Renewable Energy - ScienceAlert.” http://www.sciencealert.com/underwater-balloons-could-give-us-a-new-way-of-storing-renewable-energy.

Natural Resources Defense Council. 2009. “How Much Water Is Being Lost Throughout CA?” White Paper. Water System Optimization.

Olson, C. M. (1999). Nutrition and health outcomes associated with food insecurity and hunger. The Journal of Nutrition, 129(2S Suppl), 521S–524S.

Parfitt, J., M. Barthel, and S. Macnaughton. 2010. “Food Waste within Food Supply Chains: Quantification and Potential for Change to 2050.” *Philosophical Transactions of the Royal Society B: Biological Sciences* 365 (1554): 3065–81. doi:10.1098/rstb.2010.0126.

Pirog, R., Van Pelt, T., Enshanyan, K., and Cooke, E. (2001). Food, fuel and freeways: An Iowa perspective on how far food travels, final usage, and greenhouse gas emission. Retrieved October 15, 2001 from www.ag.iastate.edu/centers/leopold

Pohl, Christian, Stephan Rist, Anne Zimmermann, Patricia Fry, Ghana S Gurung, Flurina Schneider, Chinwe Ifejika Speranza, et al. 2010. “Researchers’ Roles in Knowledge Co-Production: Experience from Sustainability Research in Kenya, Switzerland, Bolivia and Nepal.” *Science and Public Policy* 37 (4): 267–81. doi:10.3152/030234210X496628.

Pooley, J. A., and M. O’Connor. 2000. “Environmental Education and Attitudes: Emotions and Beliefs Are What Is Needed.” *Environment and Behavior* 32 (5): 711–23. doi:10.1177/0013916500325007.

Poonpun Piyasak, and Ward T. Jewell. 2008. “Analysis of the Cost per Kilowatt Hour to Store Electricity.” Vol. 23, No. 2. IEEE TRANSACTIONS ON ENERGY CONVERSION. IEEE.

Qi, Yinan, Ned Beecher, and Lori Stone. 2013. “A National Survey of Biogas Use at Wastewater Treatment Plants in the United States: The Results.” *Proceedings of the Water Environment Federation* 2013 (5): 655–66. doi:10.2175/193864713813536778.

Rabbani, T., Munier, S., Dorchies, Malaterre, P., Bayen, A., and Litorico, X. (2009). Flatness-based control of open-channel flow in an irrigation canal using SCADA [Applications of Control]. Control Systems, IEEE 29.5: 22-30.

Rewe Sustainability Report. 2012. “Annual Report 2012 - REWE Group.” http://www.rewe-group-geschaeftsbericht.de/2012/en/.

Rhoten, D. 2004. “EDUCATION: Risks and Rewards of an Interdisciplinary Research Path.” *Science* 306 (5704): 2046–2046. doi:10.1126/science.1103628.

Rickinson, Mark. 2001. “Learners and Learning in Environmental Education: A Critical Review of the Evidence.” *Environmental Education Research* 7 (3): 207–320. doi:10.1080/13504620120065230.

Ringler, C., Bhaduri, A., Lawford, R. (2013). The nexus across water, energy, land and food (WELF): Potential for improved resource efficiency? Current Opinion in Environmental Sustainability 5 (6), S. 617-624. DOI: 10.1016/j.cosust.2013.11.002

Roach, John. 2015. “For Storing Electricity, Utilities Are Turning to Pumped Hydro by John Roach: Yale Environment 360.” http://e360.yale.edu/feature/for_storing_electricity_utilities_are_turning_to_pumped_hydro/2934/.

Robertson, W. D., and L. C. Merkley. 2009. "In-Stream Bioreactor for Agricultural Nitrate Treatment." *Journal of Environment Quality* 38 (1): 230. doi:10.2134/jeq2008.0100.

Rose, D. (1999). Economic determinants and dietary consequences of food insecurity in the United States. The Journal of Nutrition, 129(2S Suppl), 517S–520S.

Schoups, G., J. W. Hopmans, C. A. Young, J. A. Vrugt, W. W. Wallender, K. K. Tanji, and S. Panday. 2005. "Sustainability of Irrigated Agriculture in the San Joaquin Valley, California." *Proceedings of the National Academy of Sciences* 102 (43): 15352–56. doi:10.1073/pnas.0507723102.

SEI. 2011. "Bonn2011 Conference The Water, Energy and Food Security Nexus Solutions for the Green Economy." In . Bonn: Stockholm Environment Institute.

Shen, Junyi, and Tatsuyoshi Saijo. 2009. "Does an Energy Efficiency Label Alter Consumers' Purchasing Decisions? A Latent Class Approach Based on a Stated Choice Experiment in Shanghai." *Journal of Environmental Management* 90 (11): 3561–73. doi:10.1016/j.jenvman.2009.06.010.

Tacoli, Cecilia. 1998. "Rural-Urban Interactions: A Guide to the Literature." Vol. 10, No. 1. Environment and Urbanization.

Tarpeh. 2015. *Berkeley Student Turns Urine into Fertilizer to Feed the World*. https://www.youtube.com/watch?time_continue=199&v=WBxLwdQ5s6k.

UC Davis. 2012. "Addressing Nitrate in California's Drinking Water." Implementation of Senate Bill X2 1. Groundwater Nitrate Project. http://groundwaternitrate.ucdavis.edu/files/138956.pdf.

UC Davis. 2015. "Drought Costs California Agriculture $1.84B and 10,100 Jobs in 2015." http://news.ucdavis.edu/search/news_detail.lasso?id=11281.

United Nations Department of Economic and Social Affairs. 2014. "World's Population Increasingly Urban with More than Half Living in Urban Areas | UN DESA | United Nations Department of Economic and Social Affairs." https://www.un.org/development/desa/en/news/population/world-urbanization-prospects.html.

US Bureau of Labor Statistics. (2015). Consumer Expenditures in 2013.

US Energy Information Administration. 2009. "State Fact Sheets on Household Energy Use." *RESIDENTIAL ENERGY CONSUMPTION SURVEY (RECS)*. http://www.eia.gov/consumption/residential/reports/2009/state_briefs/. (Posted in 2013)

US Energy Information Administration. 2015. "How Much Electricity Does an American Home Use? - FAQ - U.S. Energy Information Administration (EIA)." https://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3.

USDA. 2015a. USDA Economic Research Service - Farm Income and Wealth Statistics. Retrieved March 26, 2015, from http://www.ers.usda.gov/data-products/farm-income-and-wealth-statistics/annual-cash-receipts-by-commodity.aspx

USDA. 2015b. *Climate Change, Global Food Security, and the U.S. Food System*. Food Security.

Vekshin. 2014. "California Water Prices Soar for Farmers as Drought Grows - Bloomberg Business." http://www.bloomberg.com/news/articles/2014-07-24/california-water-prices-soar-for-farmers-as-drought-grows.

Vlek, Charles, and Linda Steg. 2007. "Human Behavior and Environmental Sustainability: Problems, Driving Forces, and Research Topics." *Journal of Social Issues* 63 (1): 1–19. doi:10.1111/j.1540-4560.2007.00493.x.

Vogel, Coleen, Susanne C. Moser, Roger E. Kasperson, and Geoffrey D. Dabelko. 2007. "Linking Vulnerability, Adaptation, and Resilience Science to Practice: Pathways, Players, and Partnerships." *Global Environmental Change* 17 (3-4): 349–64. doi:10.1016/j.gloenvcha.2007.05.002.

Walker, Michael E., Zhen Lv, and Eric Masanet. 2013. "Industrial Steam Systems and the Energy-Water Nexus." *Environmental Science & Technology* 47 (22): 13060–67. doi:10.1021/es403715z.

Wallander, S. (2014). California Drought 2014: Farm and Food Impacts. Retrieved March 26, 2015, from http://ers.usda.gov/topics/in-the-news/california-drought-2014-farm-and-food-impacts.aspx

Wang, Chaojun, Boshu He, Shaoyang Sun, Ying Wu, Na Yan, Linbo Yan, and Xiaohui Pei. 2012. "Application of a Low Pressure Economizer for Waste Heat Recovery from the Exhaust Flue Gas in a 600 MW Power Plant." *Energy* 48 (1): 196–202. doi:10.1016/j.energy.2012.01.045.

Ward, F. A., and M. Pulido-Velazquez. 2008. "Water Conservation in Irrigation Can Increase Water Use." *Proceedings of the National Academy of Sciences* 105 (47): 18215–20. doi:10.1073/pnas.0805554105.

Water Systems Optimization, Inc. 2009. "How Much Water Is Being Lost Throughout CA?" 2009. White Paper. Water System Optimization.

Webber, Michael E. 2008. "Catch-22: Water vs. Energy." *Scientific American* 18 (4): 34–41. doi:10.1038/scientificamericanearth0908-34.

Weichselgartner, Jürgen, and R.E. Kasperson. 2010. "Barriers in the Science-Policy-Practice Interface: Toward a Knowledge-Action-System in Global Environmental Change Research." 20, No. 2. Global Environmental Change.

Welle et al. 2015. "Testing the Waters: A Qualitative Comparative Analysis of the Factors Affecting Success in Rendering Water Services Sustainable Based on ICT Reporting." Brighton: IDS.

Williams, A. T., D. H. Zitomer, and B. K. Mayer. 2015. “Ion Exchange-Precipitation for Nutrient Recovery from Dilute Wastewater.” *Environ. Sci.: Water Res. Technol.* 1 (6): 832–38. doi:10.1039/C5EW00142K.

Wittman, Hannah. 2009. “Reworking the Metabolic Rift: La Vía Campesina, Agrarian Citizenship, and Food Sovereignty.” *Journal of Peasant Studies* 36 (4): 805–26. doi:10.1080/03066150903353991.

Wortman, Sam E., and Sarah Taylor Lovell. 2013. “Environmental Challenges Threatening the Growth of Urban Agriculture in the United States.” *Journal of Environment Quality* 42 (5): 1283. doi:10.2134/jeq2013.01.0031.